DREAM

Dynamic Response of the Environment at the Moon

Redistribution of lunar polar water to mid-latitudes and its role in forming an OH veneer – Revisited

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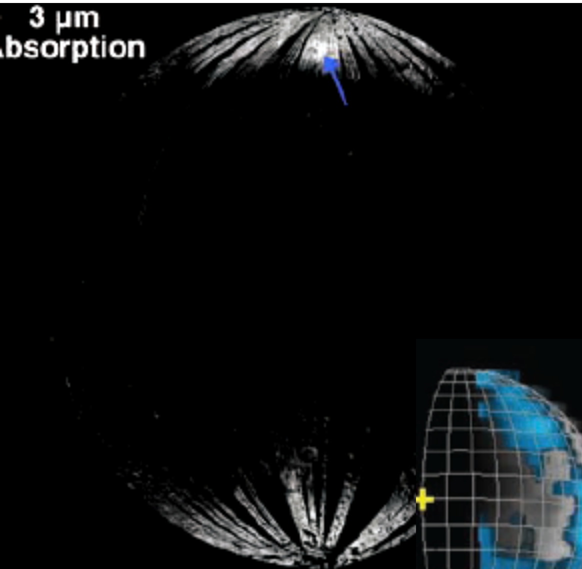
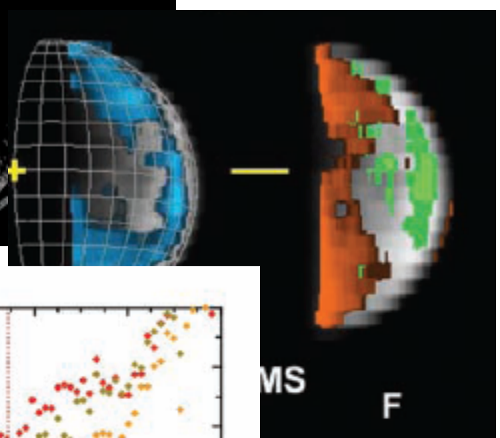
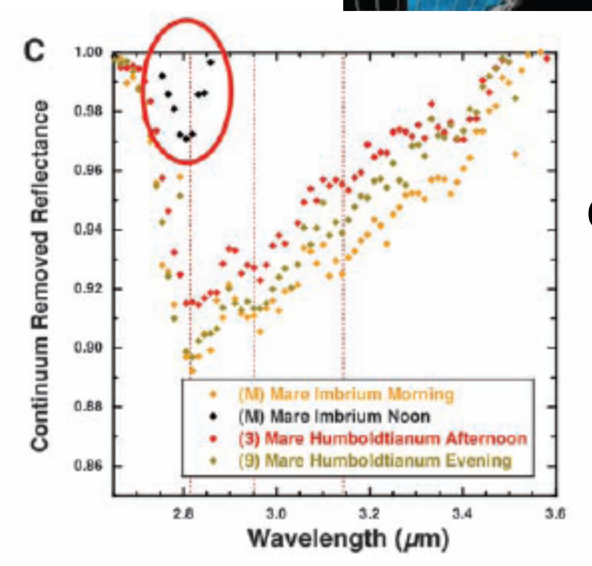
2009! – The Discovery of an OH Mid-Latitude Veneer



Pieters et al [2009]



Clark et al [2009



Sunshine et al [2009]

- Publication of Chandrayaan-1 M^3 [Pieters et al., 2009], Cassini VIMS [Clark et al. 2009], and EPOXI HRI-IR [Sunshine et al., 2009] IR observations of OH/water content in near-surface of regolith
- Observe an IR absorption feature near 3 micron in reflectance spectra

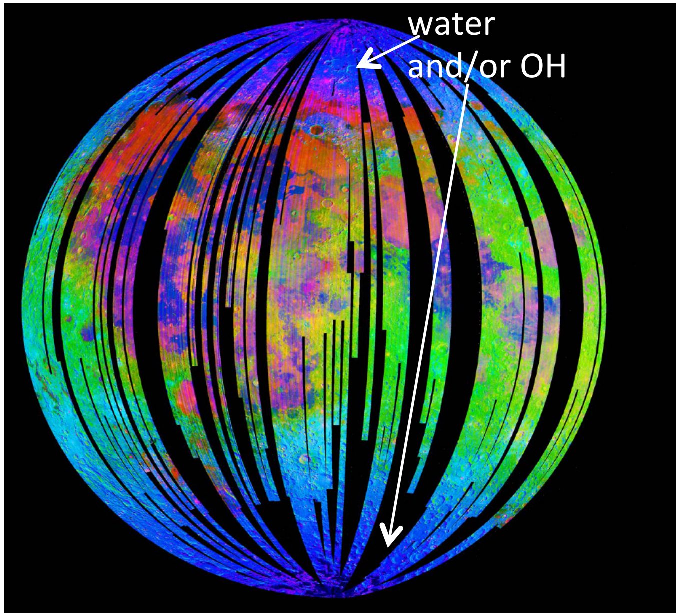
What are the possible sources of the non-polar water ?

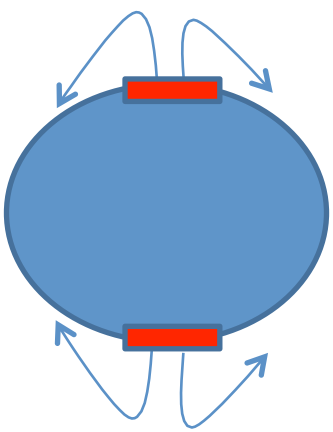
(from McCord et al., 2011)

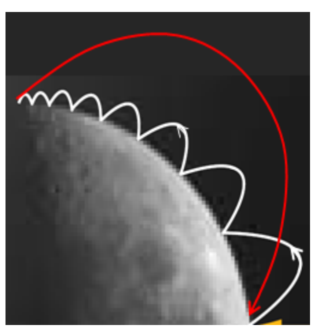
- OH in minerals (evolving view) e.g., 1000's of ppm of OH/W in lunar apatite samples [McCubbin et al., 2010], but possibly not present in significant abundances…small fraction of surface
- Cometary & Meteoric infall – some meteorites have OH bearing material
- Solar wind conversion: Energetic protons implanted into an oxygen-rich regolith [Pieters et al., 2009; Clark et al., 2009; Sunshine et al, 2009]
  - OH from implanting, OH-OH interaction release H_2O (and H_2) [Poston et al. LPSC, 2012]
  - OH from implanting, but energy from μ-meteoroid converts to water [Vondrak and Crider, 2003]
  - However, solar wind is also a sputtering loss for saturated and icy surfaces

4th Source:

Clark et al, 2010

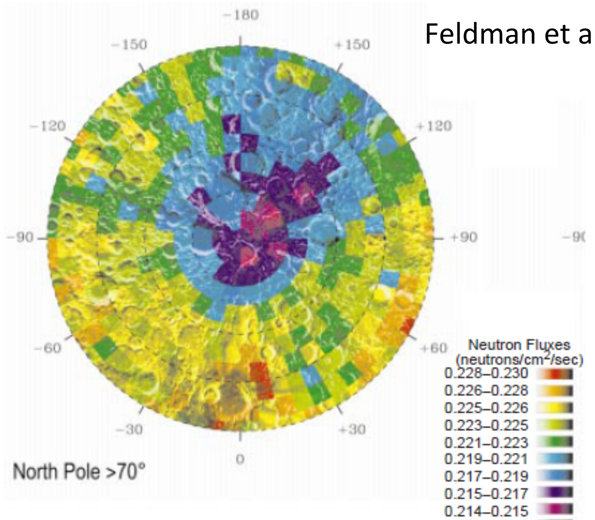




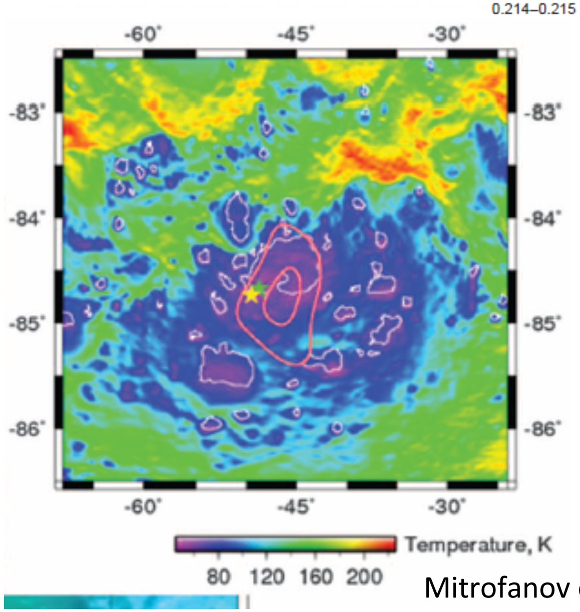


- Could icy regolith within polar craters be a dynamic source for this water veneer at mid-latitudes?
- Space environmental erosion (sputtering, impact vaporization) energetically ejects water molecules to mid-latitudes
- **Redistribution** of polar water
- Explore this hypothesis via water budget analysis

Water in Lunar Polar Cold Traps



Feldman et al., 1998

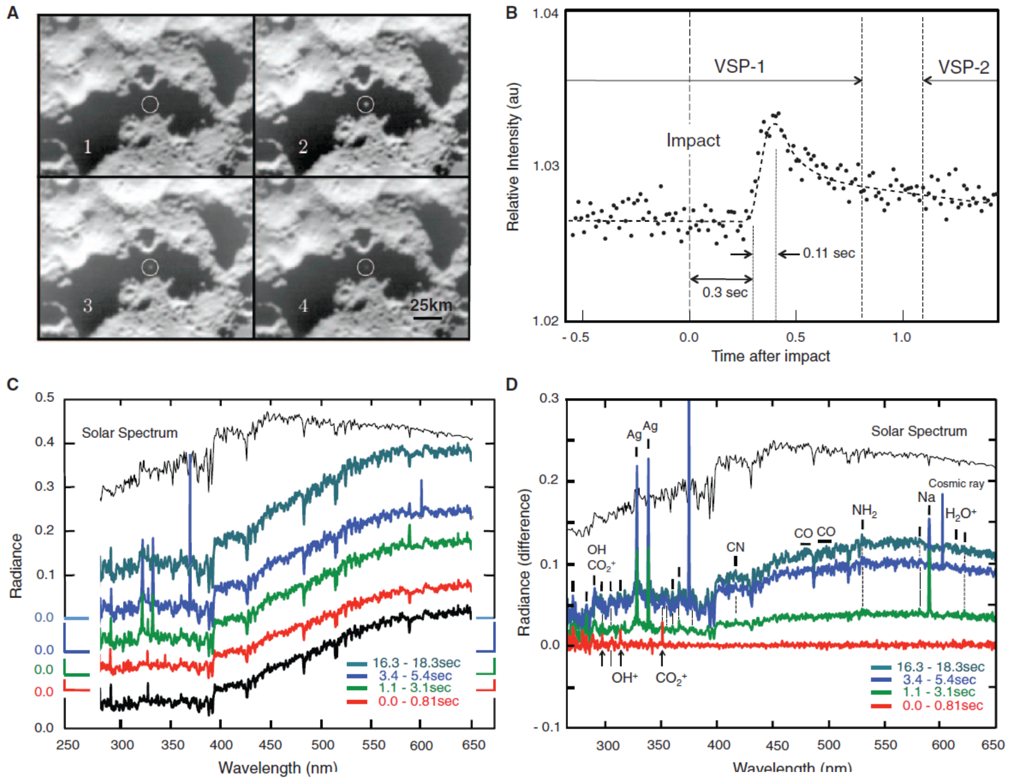


Mitrofanov et al., 2010

- Lunar Prospector Neutron Spectrometer: epithermal neutron reduction indication of H-bearing minerals (Feldman et al., 1998)
- Statistically significant reduction in lunar polar regions
- LRO/LEND (Mitrofanov et al., 2010) Neutron Suppressed Regions
  - Statistically significant NSRs in Cabeus and Shoemaker
  - H content at 300- 500 ppm
- Presence of water validated (and then some) via LCROSS

LCROSS 2009 Impact

Schultz et al 2010



- Revealed water ice and vapor in plume at about ~ 5%wt

-Plume rich in other species

-In fact, more water than LP and LEND would suggest…

-Attempt for reconciliation by Elphic et al. [2011] "Did LCROSS get lucky?"

<u>Science 2010 set:</u>

Colaprete et al

Schultz et al

Gladstone et al

Haynes et al

Paige et al

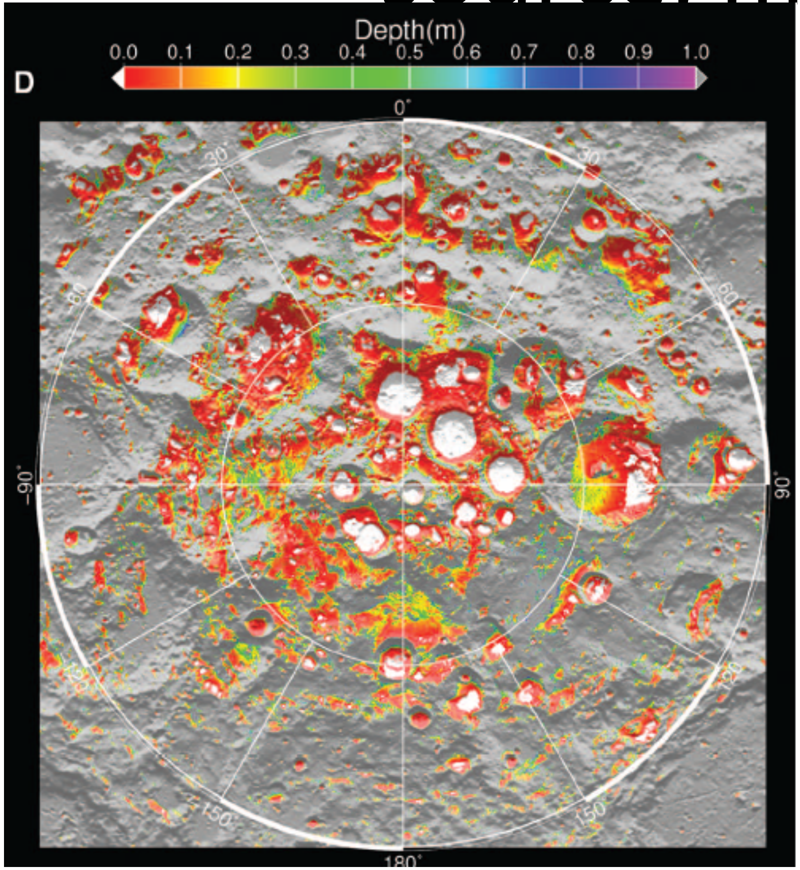
Kerr review

Table 1. Summary of the total water vapor and ice and ejecta dust in the NIR instrument FOV. Values shown are the average value across the averaging period, and errors are 1 SD.

	Water mass (kg)			
Time (s)	Gas	Ice	Dust mass (kg)	Total water %
0–23	82.4 ± 25	58.5 ± 8.2	3148 ± 787	4.5 ± 1.4
23–30	24.5 ± 8.1	131 ± 8.3	2434 ± 609	6.4 ± 1.7
123–180	52.5 ± 2.6	15.8 ± 2.2	942.5 ± 236	7.2 ± 1.9
Average	53 ± 15	68 ± 10	2175 ± 544	5.6 ± 2.9

Colaprete et al. 2010

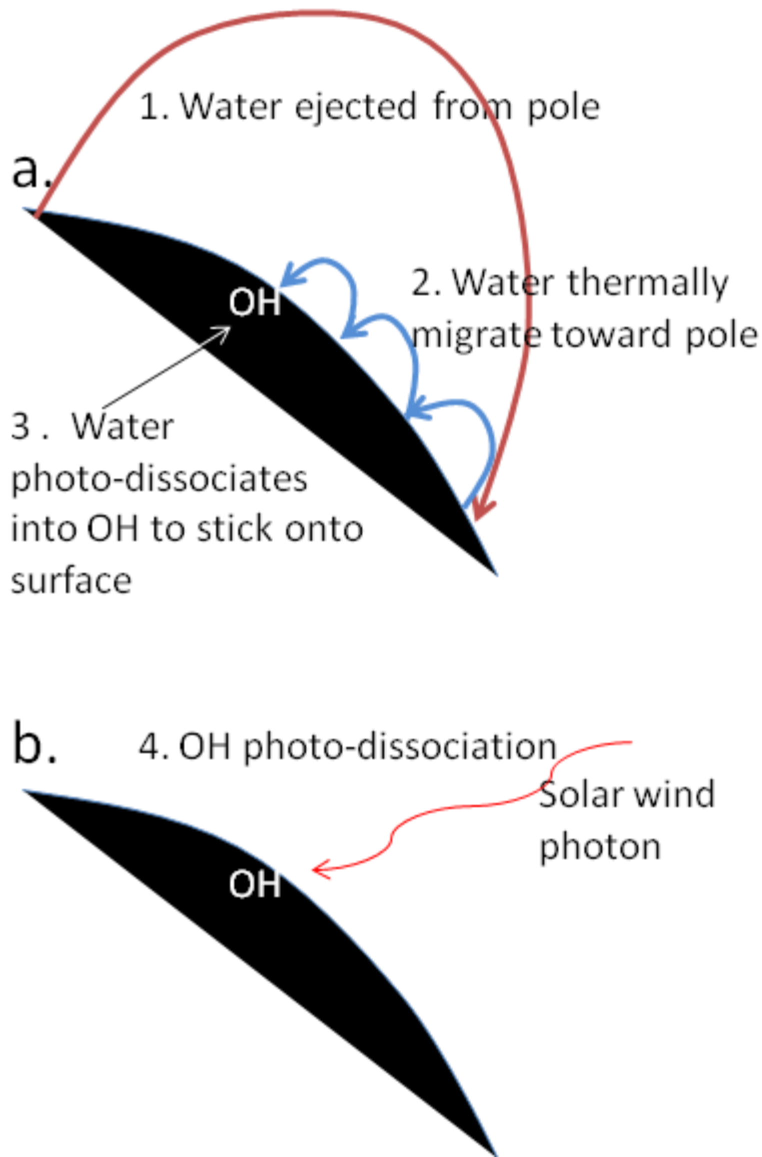
Given the complicated polar crater source, make two models:



Water Thermal Stability Model
Paige et al 2010
White areas= water stable at surface
Orange areas= water stable in first 10 cm

- Model #1 – Surficial and subsurface ice/regolith mix at 0.1%wt water
- Model #2- Buried ice/ regolith mix at 5%wt water
- Water only within polar craters: A ~ $10^{10}/m^2$ (in SP, it's the combined area of larger craters)

Polar Water Fountain Concept



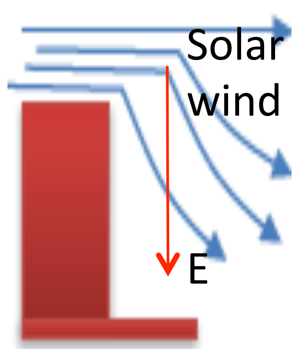
Processes that weather & liberate icy-regolith in polar craters (Model #1)

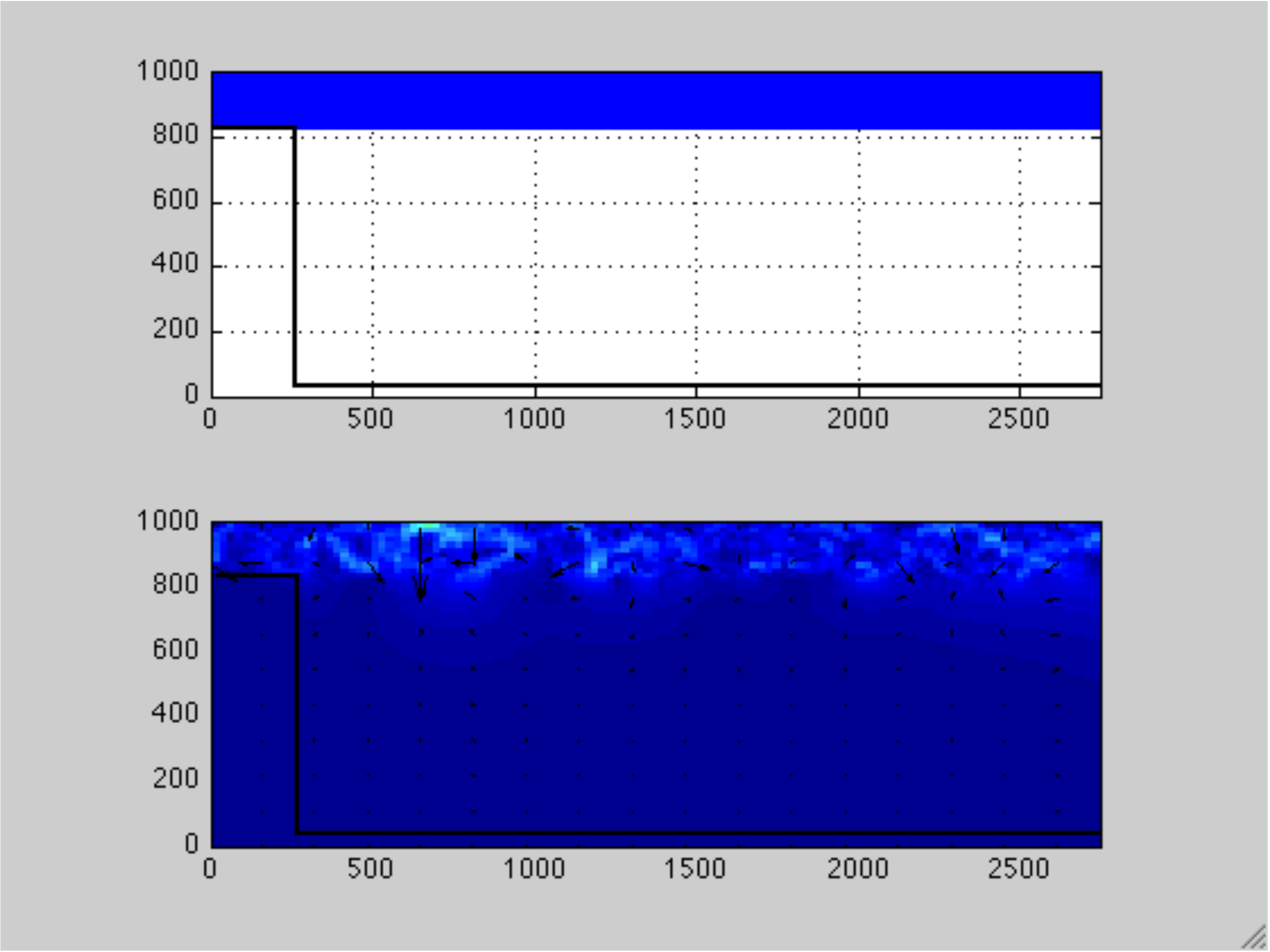
- **Sputtering** – ~1 keV proton yield for 0.1%wt water is Y~ 10^{-3} [Johnson, 1990], ion flux defined by polar crater SW inflow models [Zimmerman et al., 2011]
- **Electron Stimulated Desorption –** Thrower et al. [2010] provided cross-sections (yield determined for water at 0.1%) , electron flux defined by polar crater SW inflow models[Zimmerman et al. 2011]
- **Photon (Lyman -α) Stimulated Desorption –** Thrower et al. [2010] also provided cross sections (yield determined for water at 0.1%), apply flux from background Ly-α [Gladstone et al., 2012]
- **Impact Vaporization-** Micro-meteoroid yield is typically 10^{-15} kg/m^2-s [Cintala,1992]. For 0.1% icy-regolith, water outflux at 3×10^7 H_2Os/m^2-s

Example: Sputtering: Polar Crater Solar Wind Inflow

Horizontally-flowing solar wind deflected into polar craters via ambipolar E-fields
Zimmerman et al. 2011 and 2012

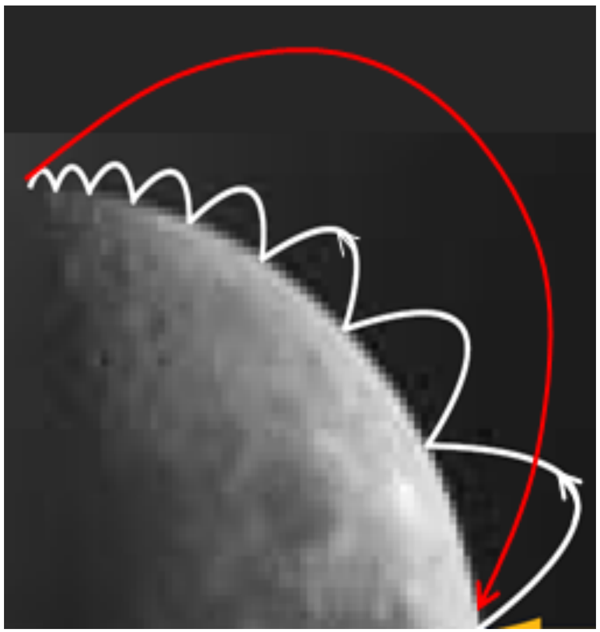
-Electrons move in ahead of ions
-Create ambipolar E
-E drives ion in





These deflected ions now a sputtering source

Energization and Transport Mechanisms



Modification of Vondrak and Crider (2003) figure

- Eject: Sputtering
  - $1/E^2$ energy
  - Escape, but some H2Os will be ballistic
  - Solar wind ions at oblique angles
  - polar craters: ion flux can be reduced1/10000
  - Penetration < 100 Angstroms in depth

- Eject: Impact Vaporization
  - T ~ 4000K
  - Eject water at v ~2km/sec
  - ~400 km altitude,
  - ~800 km in one hop
  - Ability to excavate deeper into regolith

- Return: Thermal migration (Butler, 1997; Crider and Vondrak, 2000)
- Very dynamic situation

Processes that weather icy-regolith in polar craters (Model #1)

0.1%wt water icy-regolith at surface

	Yield (H_2O/event)	F ($1/m^2$-s)	$S = YFA_s$ (H_2Os/s) [4]
SW Ion Sputtering	10^{-3} [5]	$< 2 \times 10^{11}$	3×10^{18}
ESD	2×10^{-5} [1]	$< 10^{12}$	$< 2 \times 10^{17}$
PSD Cosmic Ly-α	2×10^{-6} [1]	5×10^{12}	10^{17}
Impact Vaporization[2]	3×10^{14} [3]	$\sim 10^{-7}$ [3]	3×10^{17} [2]

1. Cross section from Thrower et al, 2010; ; Surface density ($n^{2/3}$) for 0.1%wt icy regolith
2. Cintala 1992, total vaporization at 10^{-16} g/cm^2-s; into regolith with 0.1%wt of this is water
3. Cintala 1992, yield and flux for the 10^{-8} g impactor; the peak in impactor vapor flux
4. Polar Cap Source Area = 10^{10} m^2
5. Weighted Yield for water from 0.1%wt icy regolith

Note: Yield of PSD in pocket with discussion section of Gladstone et al [2012]

Processes that weather icy-regolith in polar craters (Model #2 – Buried layer)

- Assume a 5%wt icy-regolith at depth, d
- We require any impact of penetrate to 2d to get well into the icy layer
- For nominal impactor speed of ~10 km/sec, crude estimate is $M_{vapor} \sim M_{impactor}$ [Cintala, 1992]
- Crater depth-to-impactor diameter ~ 9 [Gault, 1972] so estimate impactor radius as $r_i = d/9$
- Look at layer depths of 3, 20, and 50 cm being impacted by 4×10^{-4} kg, 0.1 kg, and 1.7 kg capable of penetrating to depth of 6, 40, and 100 cm respectively
- Yield of water: $Y^{water}{}_{i} \sim 4C\rho_p r_i^3/m_w$, where water content in vapor, C is ~0.02

Processes that weather icy-regolith in polar craters (Model #2)

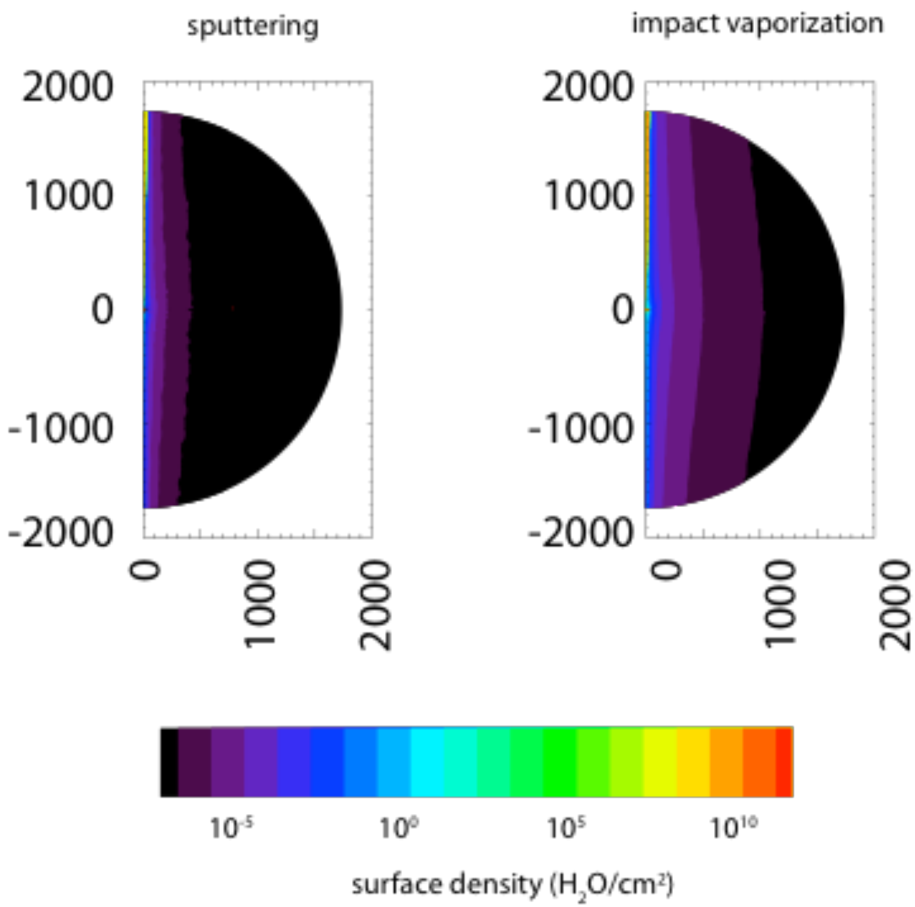
A layer of icy-regolith of 5%wt water buried at depth, d

	Ice Layer Depth (cm)	Impactor Depth (cm)	Yield (H_2O/ impact event)	F ($1/m^2$-s)	$S = YFA_s$ [3] (H_2Os/s)
Impact Vaporization	3	6	2.4×10^{20} [1]	3×10^{-14} [2]	7×10^{16}
Impact Vaporization	20	40	7×10^{22} [1]	3×10^{-17} [2]	2×10^{16}
Impact Vaporization	50	100	1×10^{24} [1]	10^{-18} [2]	1×10^{16}

1. Assuming an impact depth-to-diameter ratio = 9 [Gault, 72]; $M_{vapor} \sim M_{impactor}$ (Cintala, 1992)
2. Impact flux from Fig 5 of Meyer-Vernet et al (2009)
3. Polar Cap Source Area = 10^{10} m^2

Mildly decreasing S rate with depth

Monte Carlo Model of Veneer



- For S flux of 10^{19} water/s
- For F_w ~ 3 x 10^6 H_2Os/m^2-s
- A water surface residency time of 0.5 microseconds
- Instantaneous water surface veneer has a value of ~1 H_2Os/m^2 (or 10^{-4}/cm^2).
- Compare the M^3: Get a correct-looking spatial distribution but concentration levels too low (by a factor of over 1000)

Conclusions

- The environment does extract volatiles from the polar crater surface, but not by thermal processes like sublimation (thermal desorption)
- Instead relying on more violent processes like impact vaporization and sputtering to provide the required heat/energy for molecular transport.
- IV and sputtering are additional loss processes to consider beyond PSD by Lyman-α
- Polar water fountain CANNOT account of M^3 IR water veneer, but 'redistribution' provides some contribution at a smaller level
- LADEE can look for UV signature of released polar water flow

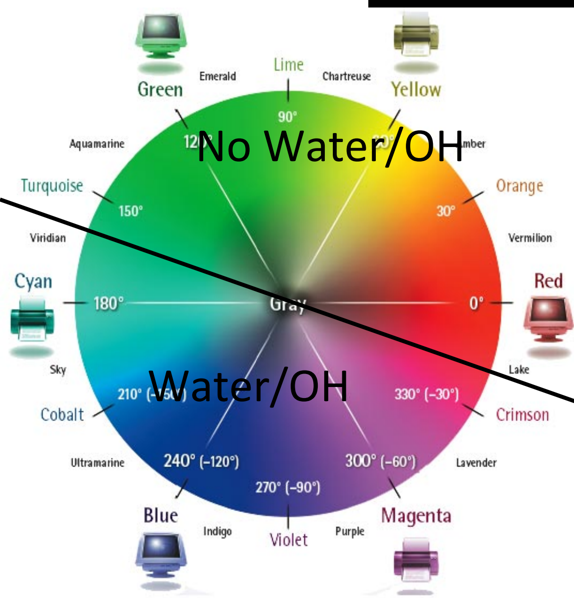
Backups

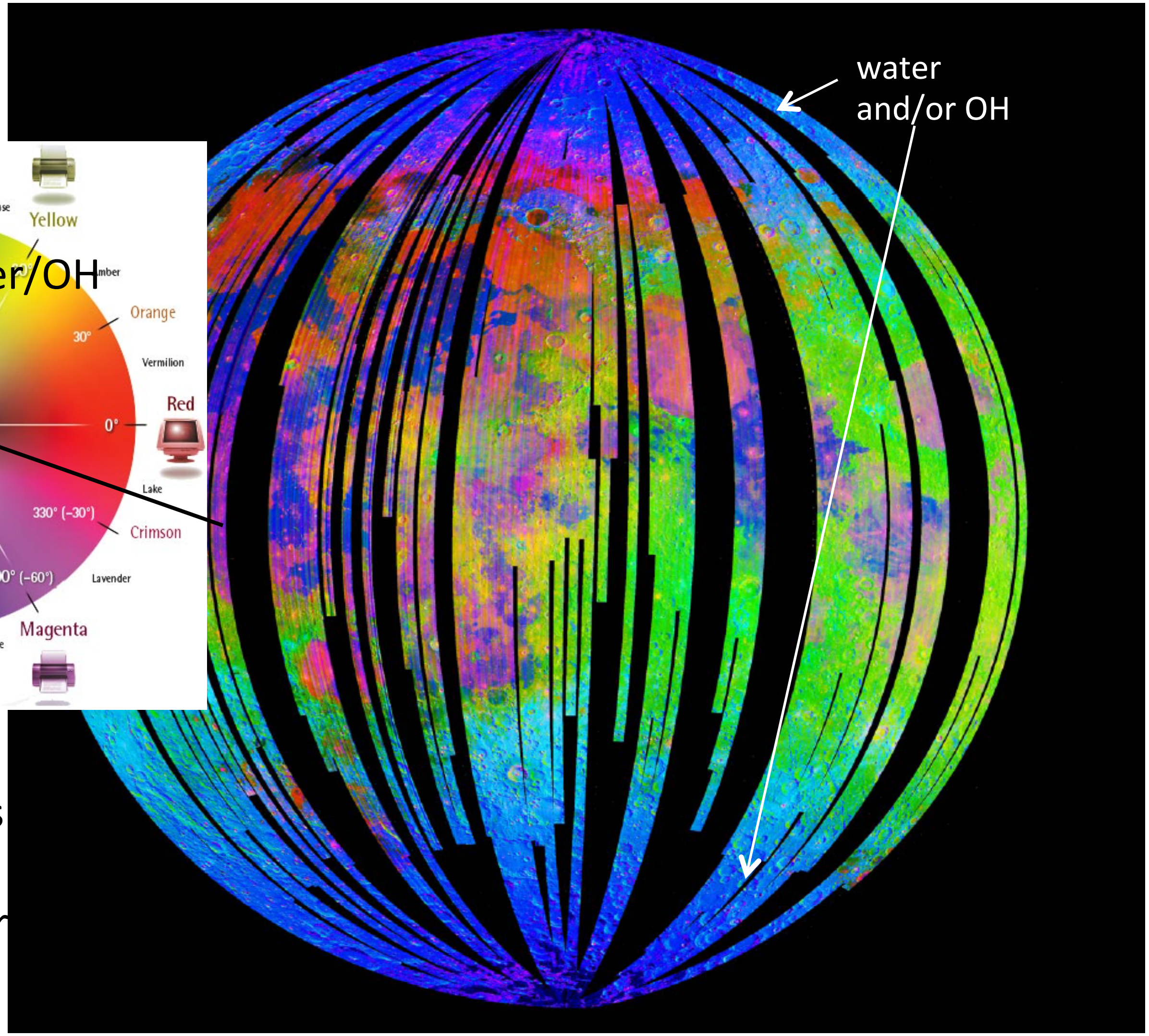
- Mike, delete the backups if you want – or you can add them to the talk as you need…

- Thanks! b

- Hurley example
- Difference in OH and H2O spatial distributions
- Nightside water collection

Clark et al, 2010



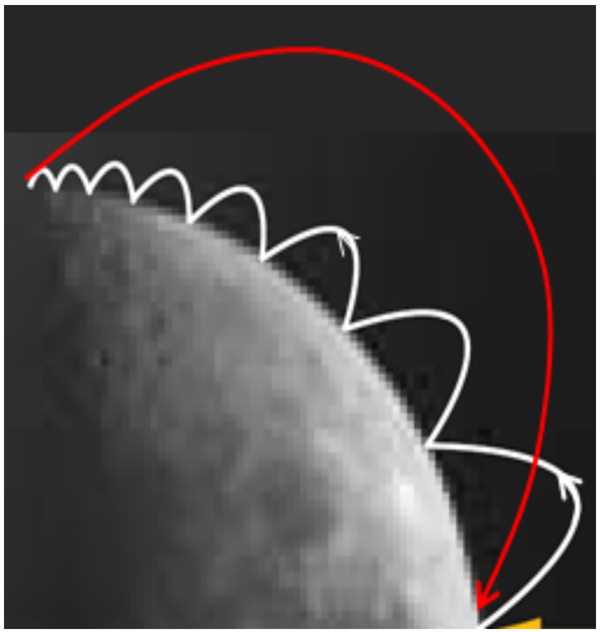


M^3 global Map

Merged elements of mineralogical signature by color

A Work of Art! - object space, negative space

LADEE Water/OH search



Modification of Vondrak and Crider (2003) figure

- Help constrain the big picture
- If water tied to mineralogy – see little/no exospheric water
- If water manufactured dynamically, LADEE might sense

For polar source scenario:

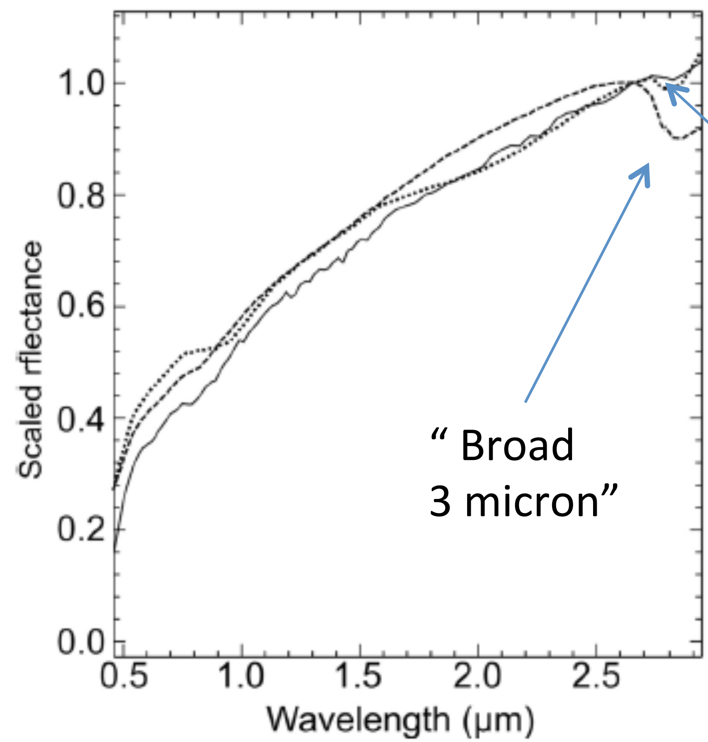
- Should expect water and OH molecules in an exosphere
- Energetic flow out of pole
- Thermalized flow into pole
- UVS can detect OH, OH^+, $H2O^+$

Outline

- Brief review of recent IR observations of water and OH at the Moon
- Suggested sources of non-polar water
- A special look dyslectic nature of solar wind water creation/destruction
- Observations and models of polar water in cold traps
- Polar crater space weathering mechanisms
- Polar crater volatile loss & transport
- Polar fountain ‘rain’ to mid-latitudes
- LADEE!
- Conclusions

McCord et al. 2011, M^3

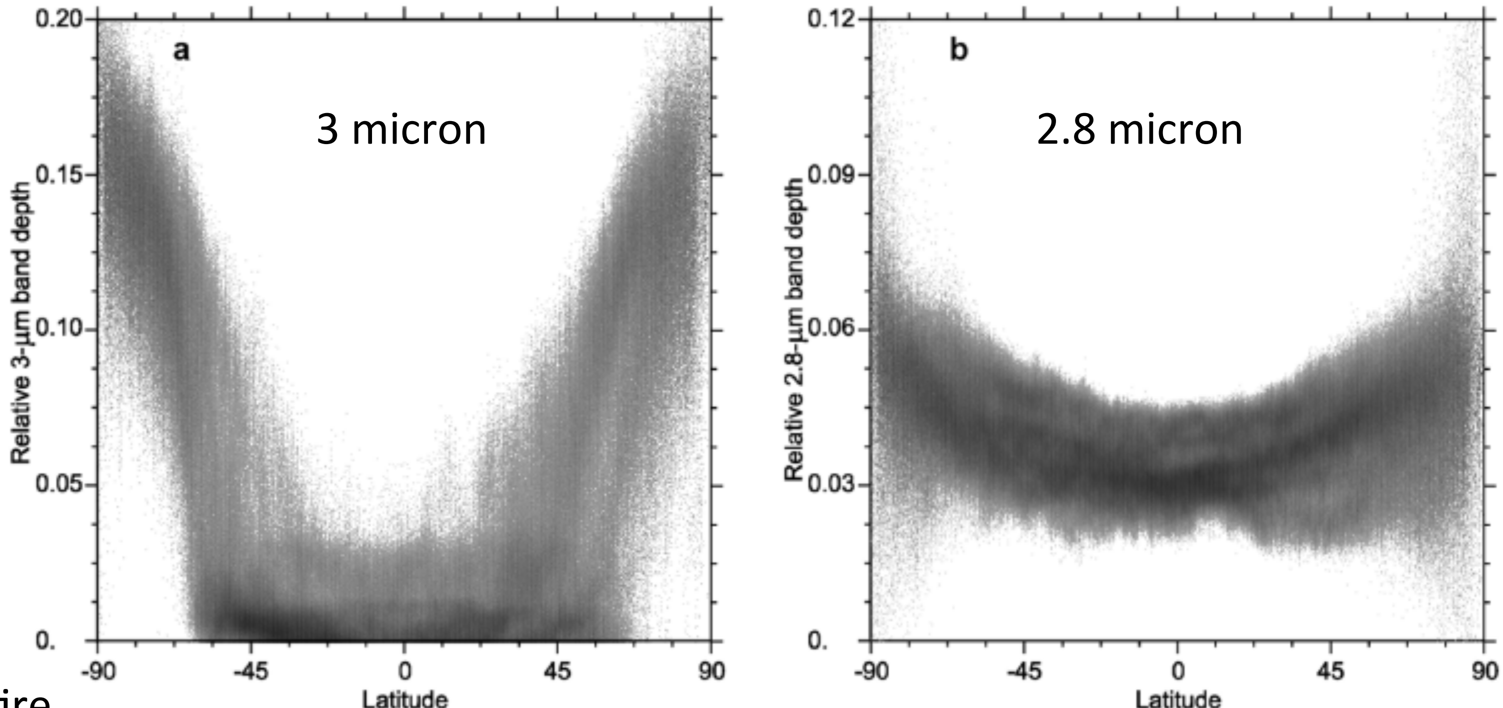
M-cubed Reflectance Spectrum



“Narrow” 2.8 micron

Figure 6. Examples of the narrower 2.8 μm (dotted line) and broader 3 μm (dashed line) absorption features in the overall M^3 Moon reflectance spectrum. The third spectrum (solid line) is for a mature highlands soil from a region where these absorptions are weak.

McCord et al. 2011, M^3



“Entire M^3 data set”

Figure 8. The strength of (left) the 3 μm versus (right) the 2.8 μm absorption features versus lunar latitude. Clearly, the behavior is different between the two absorptions. The 3 μm feature is concentrated at high latitudes and is mostly absent (as we measure it) below about 45°, with many pixels at or near zero strength and plotted on the horizontal axis. The 2.8 μm feature is present nearly everywhere with a distinct sinusoid dependence on latitude.

Water?

OH?

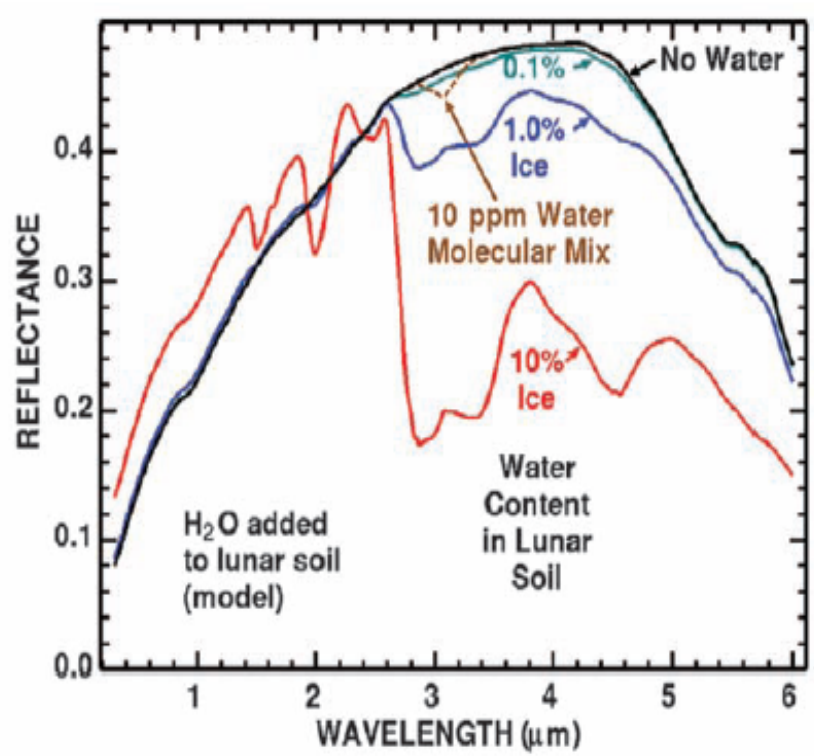
Vibration of stretched OH bonds also possible

Limited to higher latitudes

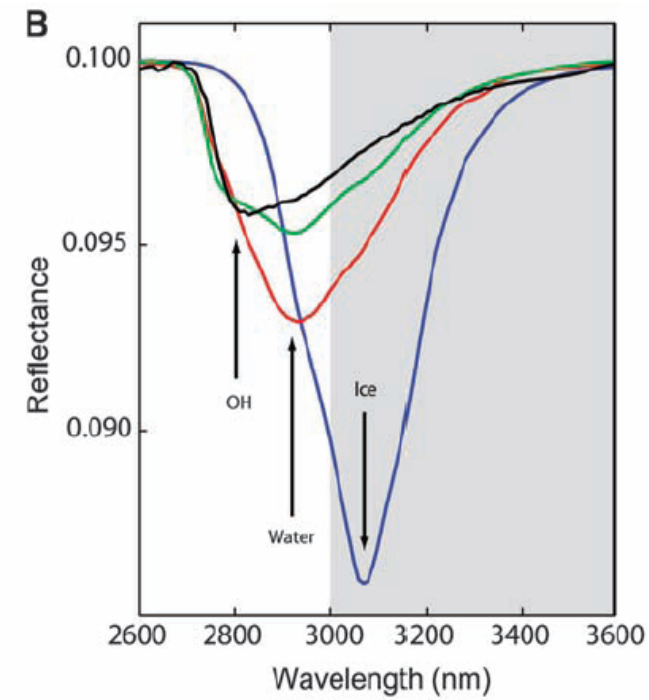
All latitudes

How much water is the IR detecting?

Fig. 3. Radiative transfer models of water and hydroxyl-bearing minerals in different conditions and amounts on a model of Apollo 16 soil (containing no water or hydroxyl absorptions). Different scattering conditions and water abundances change the strength of the 3-µm water absorption.



Clark et al, 2009



Pieters et al 2009

-Thermal emission correction at lower latitudes/affects weaker absorption features
-Nature of the 'water' – free vs bound
-Path length/grain size

Dyar et al., 2010 Grain Size & Non-uniqueness

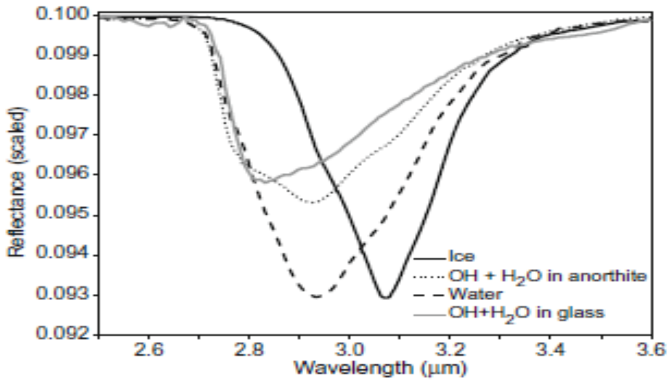
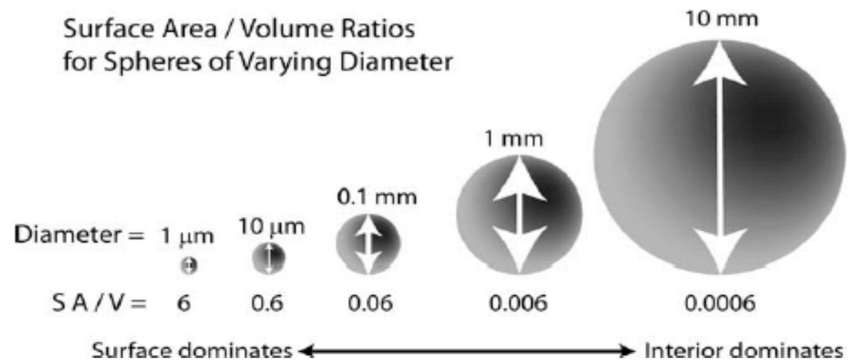


Fig. 4. Contrasting contributions from H_2O as ice and water as well as OH/H_2O in anorthite and internal water on the surface of a basaltic lunar glass analog.



A non-unique set of grain sizes, internal water, and external water that can give a common absorption feature

Scenarios for 3-μm bands in reflectance spectra.

Composition	Grain size (μm)	% Molar H_2O in interior	% Molar H_2O on surface[a]	Sampled % molar abundance H_2O
"Dry" feldspar with adsorbed water	Slab	0	0	0
	200	0	0.003	0.003
	50	0	0.012	0.012
	10	0	0.06	0.06
	1	0	0.6	0.6
"Wet" olivine with no adsorbed water	Slab	0.008	0	0.008
	200	0.008	0	0.008
	50	0.008	0	0.008
	10	0.008	0	0.008
	1	0.008	0	0.008
"Wet" pyroxene with adsorbed water	Slab	0.01	0	0.01
	200	0.01	0.003	0.013
	50	0.01	0.012	0.022
	10	0.01	0.06	0.07
	1	0.01	0.6	0.61
Aqueous-altered "dry" meteorite with 1% nontronite	Slab	0.036	0	0.036
	200	0.036	0.003	0.039
	50	0.036	0.012	0.048
	10	0.036	0.06	0.096
	1	0.036	0.6	0.636

[a] Assumes a monolayer coverage 10 Å thick.

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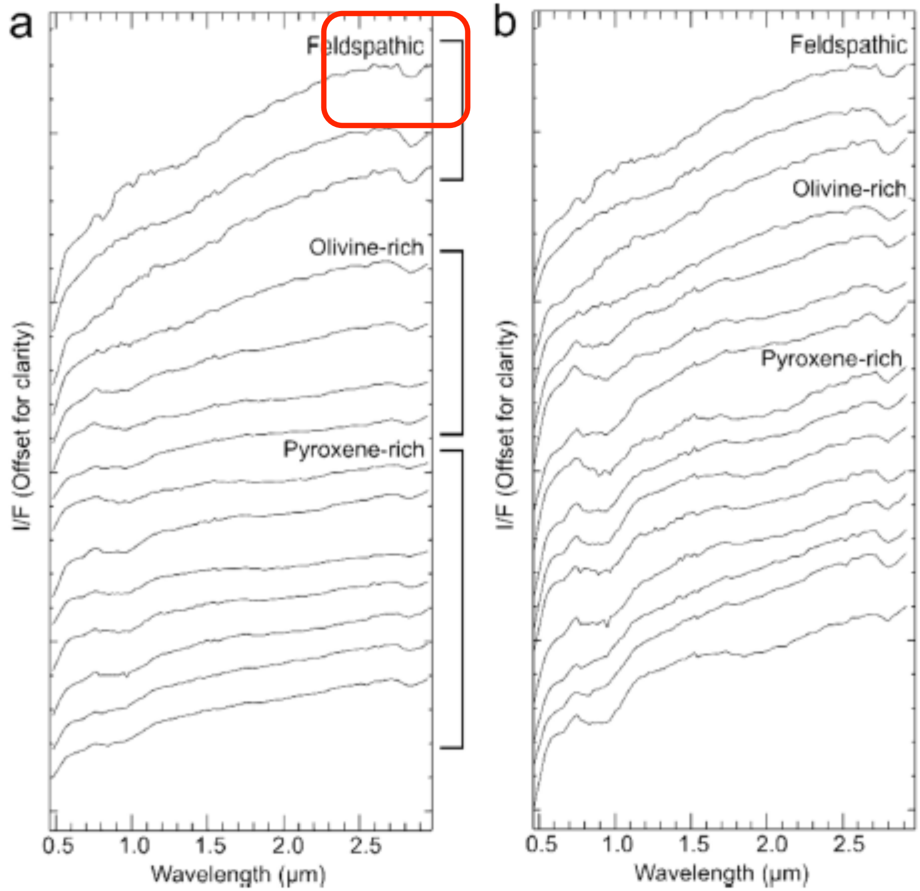
MCCORD ET AL.: OH/H_2O IN THE LUNAR SOIL FROM M^3 1



Small fresh highland craters

See 2.8 micron feature

Fresh grain micro-surface More chemically-reactive? [McCord et al 2011]

Compositional differences

Figure 11. Examples of fresh soil spectra from small fresh craters with various compositions (feldspathic, olivine-rich, and pyroxene-rich) that show absorption feature mostly at 2.8 μm. All these fresh soils are in highland regions, but the compositions vary from normal highlands felspathic to more mare-like mafic (e.g., note 1 μm region absorptions). (a) These regions differ in brightness, ranging from brightest to darkest, top to bottom. (b) However, the spectra have been scaled to have the same reflectance at 2.656 μm, thus normalizing the absorption strengths. No thermal emission has been removed, and no visual evidence of the presence of thermal radiation is apparent.

- xImplications
- xLocal water exosphere over craters & Wooden
- Example –LCROSS impact and gas plume
- xConclude- as discuss this model get to review: Water veneer story, solar wind/OH surface, Polar crater water story, Space weathering, interactions, Plasma expansion process,
- Add Zent and Burke to water story
- Explain difference in water and OH distribution

Physical/Chemical

Interaction: Plasma/Regolith Interface

SW Ions/Regolith

SW Electrons/Regolith

Deplete/Destroy Water/OH

Create/Enhance Water and OH

Physical/Chemical

Interaction: Plasma/Regolith Interface

SW Ions/Regolith

Sputtering

Implantation
(Starukhina 2006)

Y_{SiO2} ~ 0.03 molec/ion

SW Electrons/Regolith

Deplete/Destroy Water/OH

Create/Enhance Water and OH

Physical/Chemical

Interaction: Plasma/Regolith Interface

SW Ions/Regolith

Sputtering

Implantation
(Starukhina 2006)

Y_{SiO2} ~ 0.03 molec/ion

Y_{H2O} ~ 0.7 molec/ion

Erode Ice Surface
(Johnson, 1990)

$\tau \sim 10^7$ sec

Remove Surfical OH

Chemical Sputtering
(Potter, 1995)

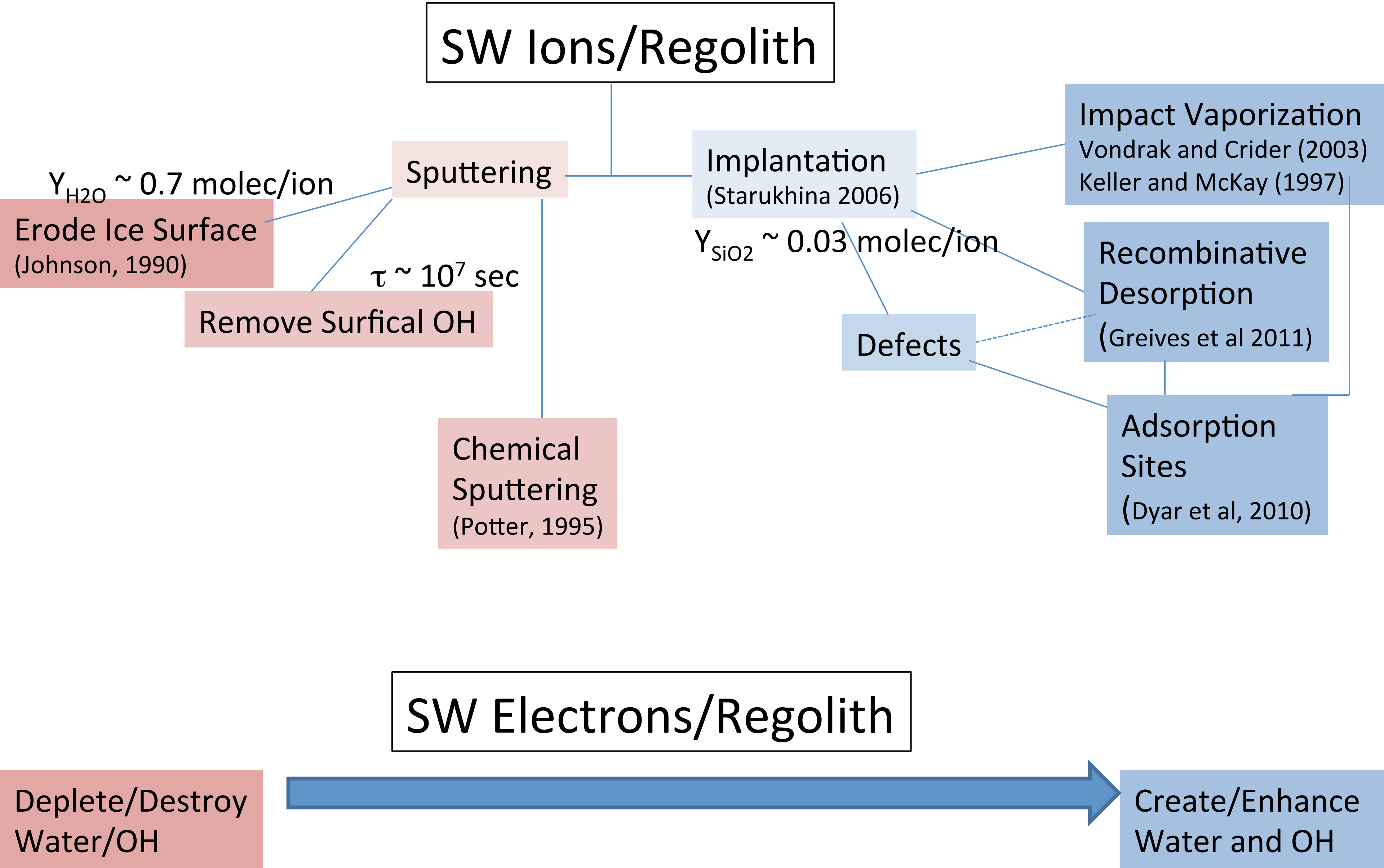
SW Electrons/Regolith

Deplete/Destroy Water/OH

Create/Enhance Water and OH

Physical/Chemical

Interaction: Plasma/Regolith Interface



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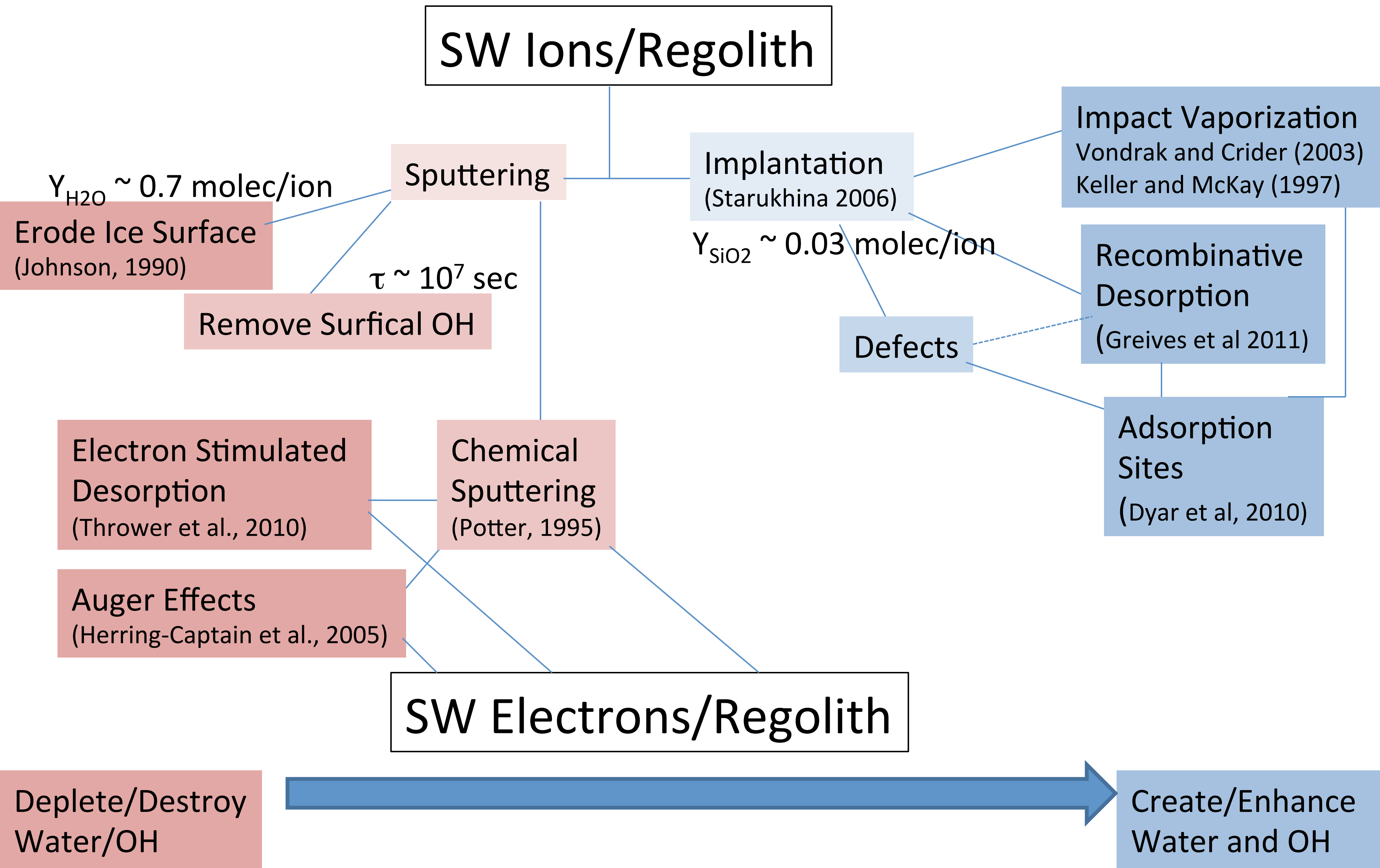

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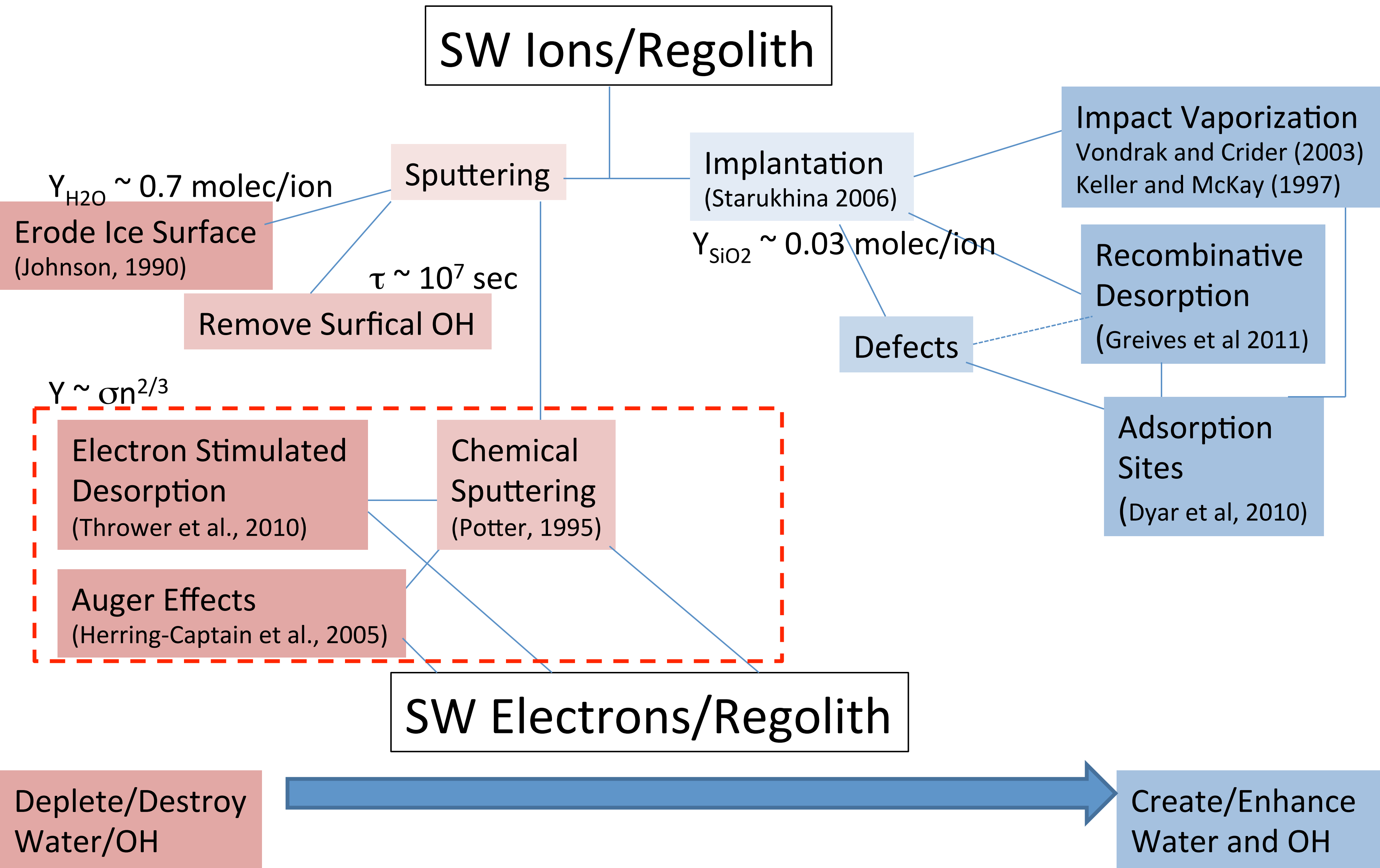
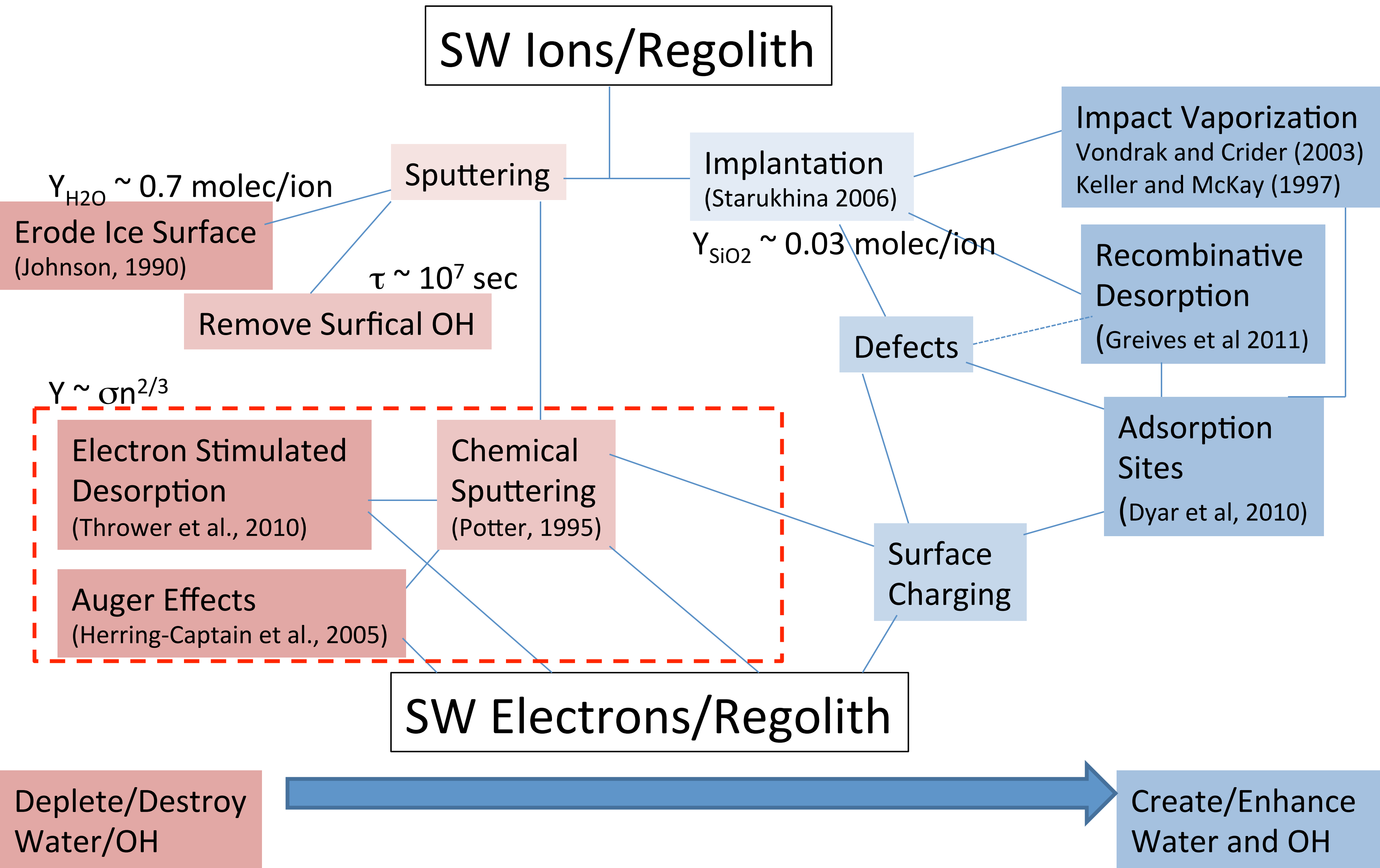


Physical/Chemical

Interaction: Plasma/Regolith Interface



Balance Sources and Losses

- No one pathway could be dominant: Not all from sputtering, not all from impact vaporization, etc….could be a balancing of multiple pathways

$$dn_{OH}/dt = \sigma_{OH}\, n_O n_H\, v_{sw} - n_{OH}/\tau_{photo} - Y_{OH}\,(5\text{Å})^2\, n_{OH} n_H\, v_{sw}$$

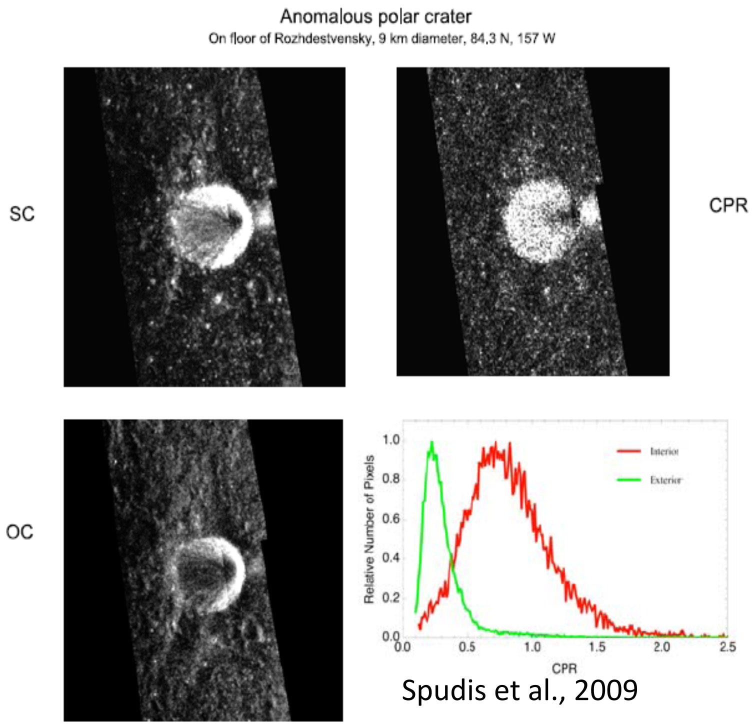
Implantation source | photo-dissociation loss | sputtering loss

- Need OH and H20 Continuity Equation

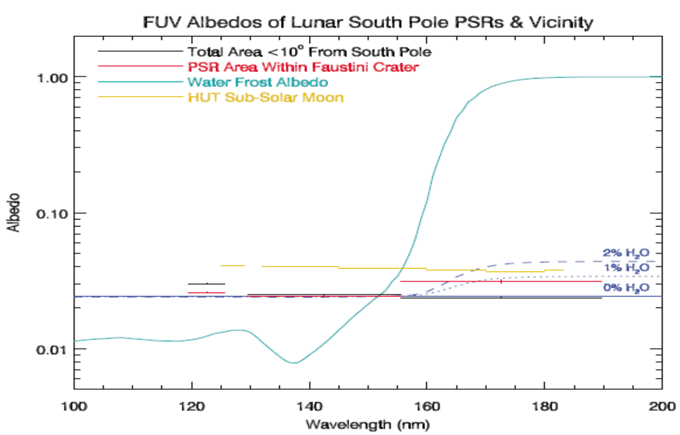
Further Support:

- Chandrayaan-1 Mini-SAR observation of unusual CPRs from north polar craters looks like (apparent) ice concentrations [Spudis et al., 2009]
- LRO-LAMP Lyman-α albedo observations of a surficial frost layer [Gladstone et al.,2012]

- LAMP, NS/LEND, Mini-SAR all probe at different depths (surface, deep, deeper)
- Possibly two water layers – 1) surfical and 2) ~10’s of cm deep….



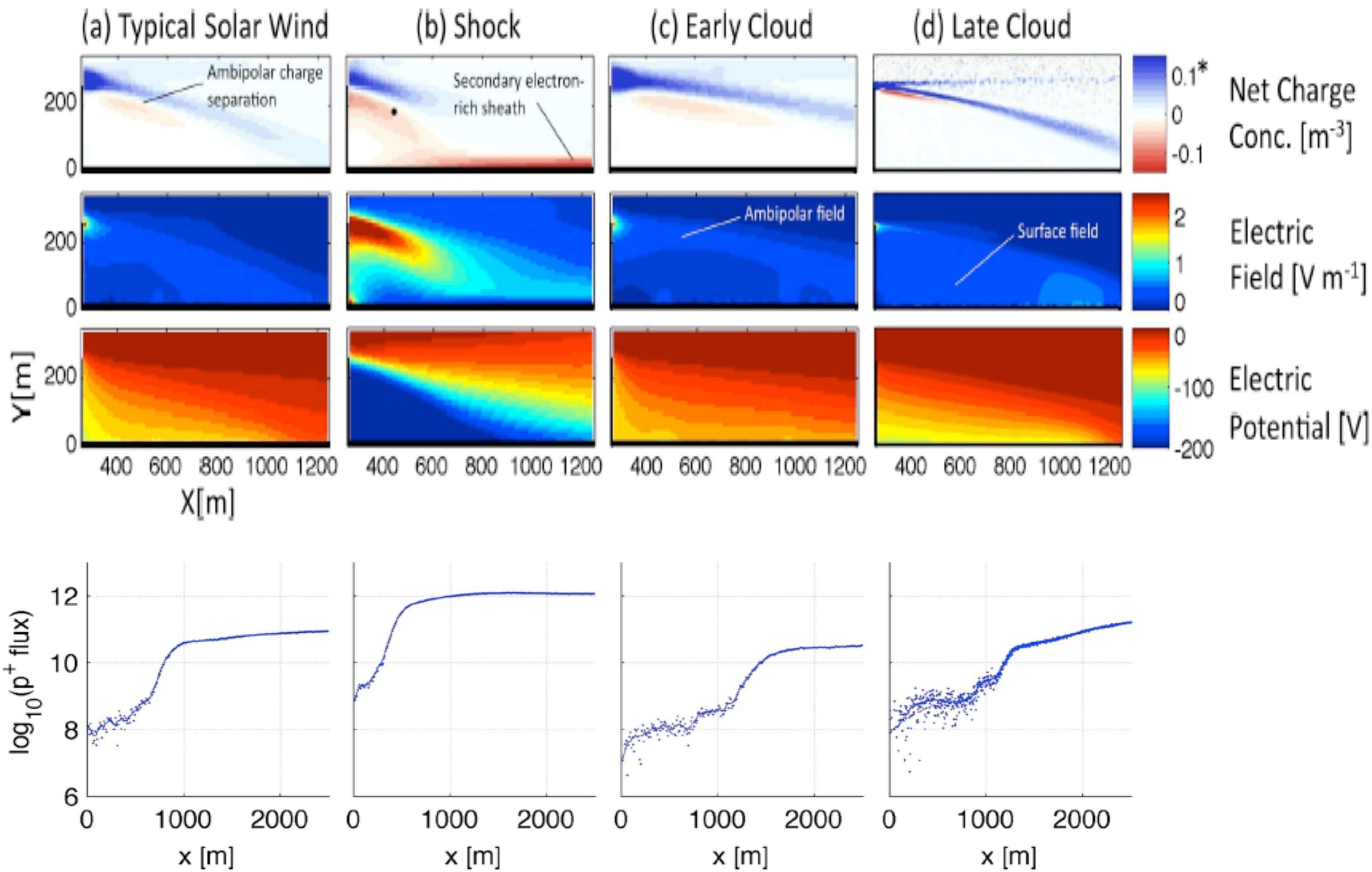
Spudis et al., 2009



Gladstone et al.,2012

Sputtering: Polar Crater Solar Wind Inflow

Zimmerman et al., 2012



Impacts: Recent Polar Crater Weathering Model [Hurley et al 2012]

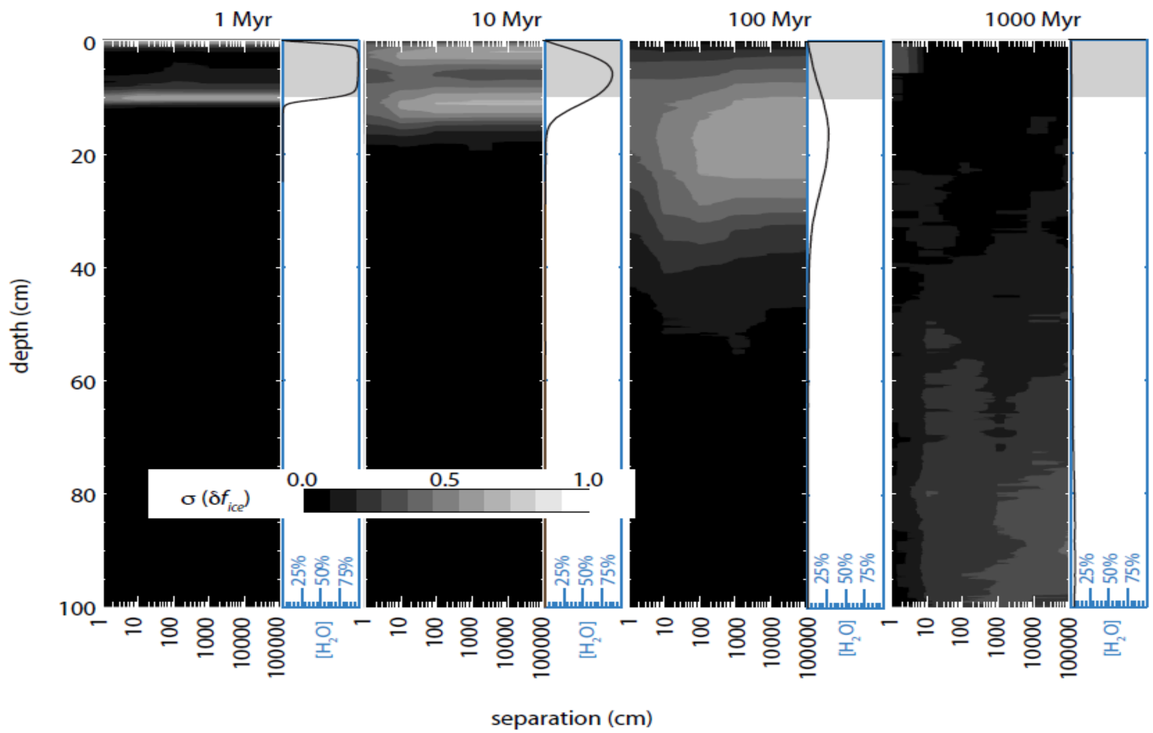


Figure 1. The standard deviation of the value of the concentration of ice as a function of depth in one column compared to another column separated by the amount on the x-axis for an ice layer that was 10 cm thick to start after (from left to right) 1 Myr, 10 Myr, 100 Myr, and 1000 Myr. For reference, the average concentration for the age is provided to the right of each plot.

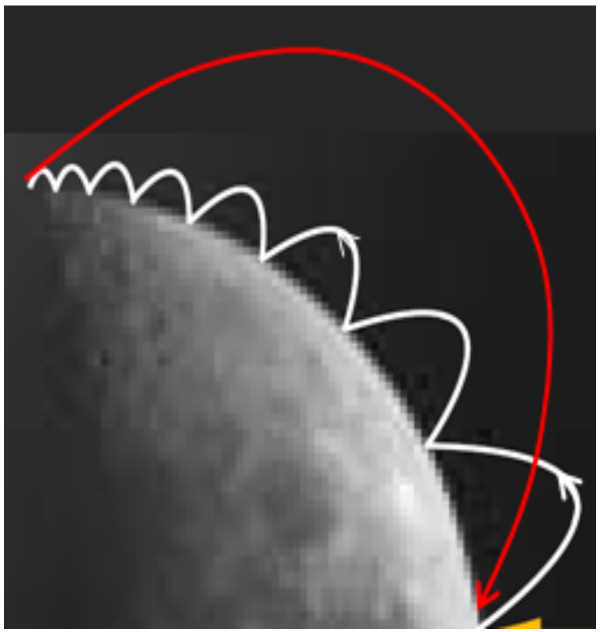
Progressively bury ice by impacts, but should also Create water vapor with Impacts

Weathering of polar ices

Atmospheric Load of the Water

- Polar source rate $S < 3 \times 10^{18}$ H2O's/s
- Water mass rate of $< 10^{-7}$ kg/s
- Released Water mass $2 S \tau_w m_w \sim 0.02$ kg where τ_w is the water lifetime (or water photo-dissociation time ($\sim 10^5$ s))
- Compared to mass of exosphere of 100 tons (Stern, 1999), this is 0.2 ppm
- Not a big load, so the effect subtle; a secondary process

Two flows of water



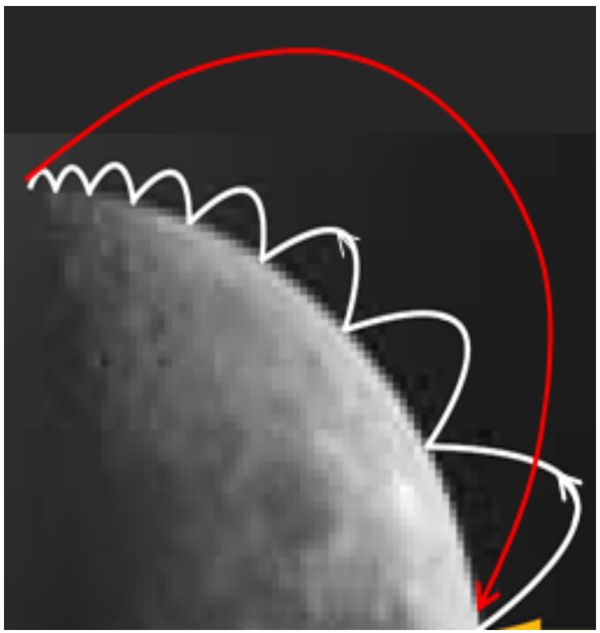
Modification of Vondrak and Crider (2003) figure

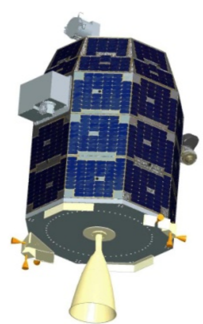
- High altitude energetic outward flow ~ 2 km/sec
- Low altitude 'pole migrating' flow at few hundred m/s (surface Ts)

Creation of a Veneer

- Total polar water source rate of 2S or 6 x 10^{18} H_2Os/sec
- Assume water distributed quasi-evenly over the mid-latitude region between 70-85^o latitude (a band of 10^{12} m^2 in the each of the north and south)
- Water mid-latitude infall becomes **F_w~ 3 x 10^6 H_2Os/m^2-s** (i.e., down-pouring rain from polar craters or side influx from lower latitudes)
- Nearly all of the H2Os photo-dissociate to OH [Crider and Vondrak, 2000], and the OH sticks to the surface until it photo-dissociates
- **In as steady-state, water influx has to equal OH losses: F_w ~ N_{OH}/τ_{OH}**, making N_{OH} ~ 3 x $10^{13}/m^2$ or **about ~ 100 OH's on each 1 micron grain**
- **Molar fraction of water ~ 3 x 10^{-8}** …much lower than observed by M^3 IR
- Polar fountain contributed to the veneer, but not dominate its formation….some other process

LADEE & The Polar Fountain OH

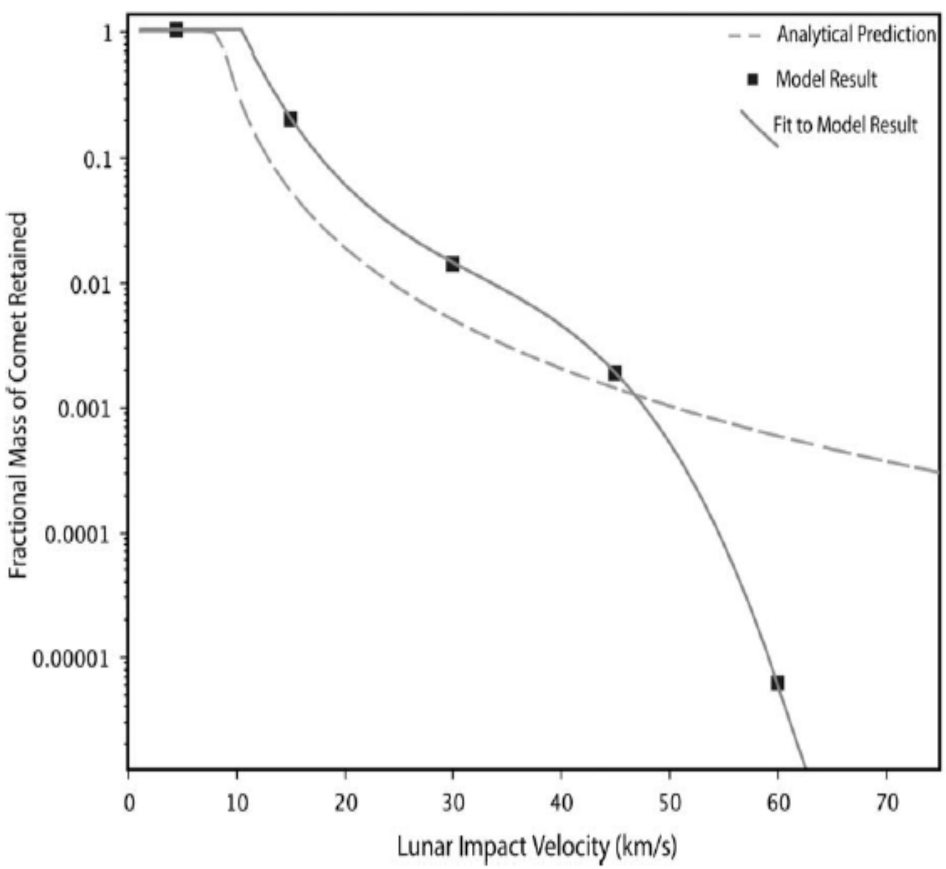




- For S ~ 3 x 10^{18} Waters/s
- Density of exospheric water at n_W ~1 H2O/m^3
- n_{OH} ~ n_W T/τ_w ~ 0.01/m^3 where T is the transit time ~ 800 sec in initial hop from pole and τ_w is the water photo-dissociation time ~10^5 s
- For LADEE UVS near equator pointing northward, with 1^o FOV, and 100 km path length, should have ~ 10^{12} waters and 10^{10} OHs along FOV…

Polar Crater Trapped Water Source

L. Ong et al. / Icarus 207 (2010) 578–589



- Judiciously sidestep a primary question: Where did the water in the polar craters come from?
- Gladstone et al [2012] water frost suggests sources and sinks nearly equal
- Comets? [Ong, et al 2010] > 10^8 tons over 1 Gya
- Just after comet release, expect rate of erosion in PCs to increase as well (if PC surface is 5%wt water, more water lost to space weathering)
- Solar wind conversion & collection [Crider and Vondrak, 2000]…less impulse, more benign
- We assume water present in craters and treat space weathering as a loss or eroding process

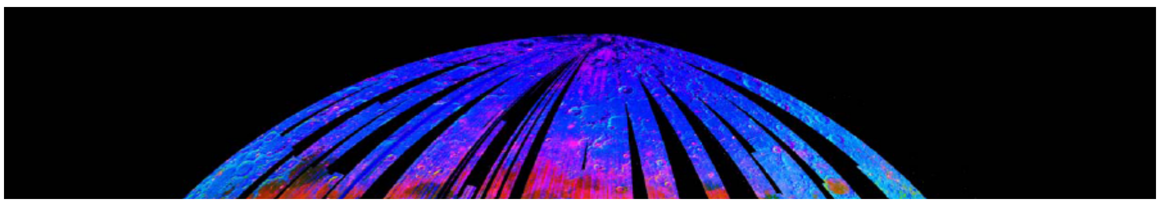
Ong et al, 2010 – as energy goes up, less comet mass retained

Model Prediction of Water Exosphere over Polar Craters

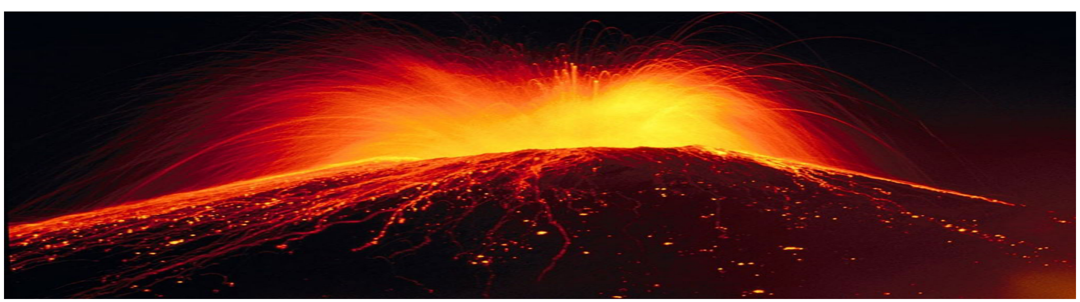
- Local exosphere of water with an upward flux of $S/A_s \sim 10^{7\text{-}8}$ waters/m^2-s directly over polar crater source regions like Shoemaker and Cabeus
- You many not have to go into the crater to get resources…they may rain down next to the crater
- A local Mg exosphere over Cabeus was observed via LCROSS prior to Centaur impact [Wooden et al. Wet v. Dry Moon, 2011]

Motivation

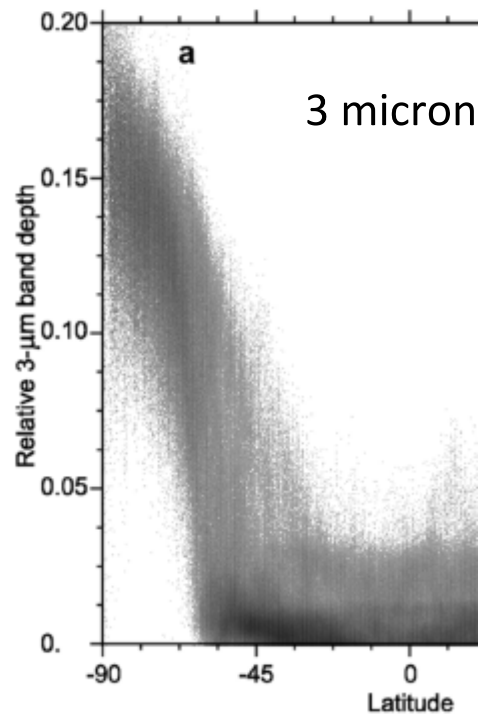
’Spillage may occur!’



Moon- spillage activated by harsh space environment



Volcano – spillage activated by geologic pressure



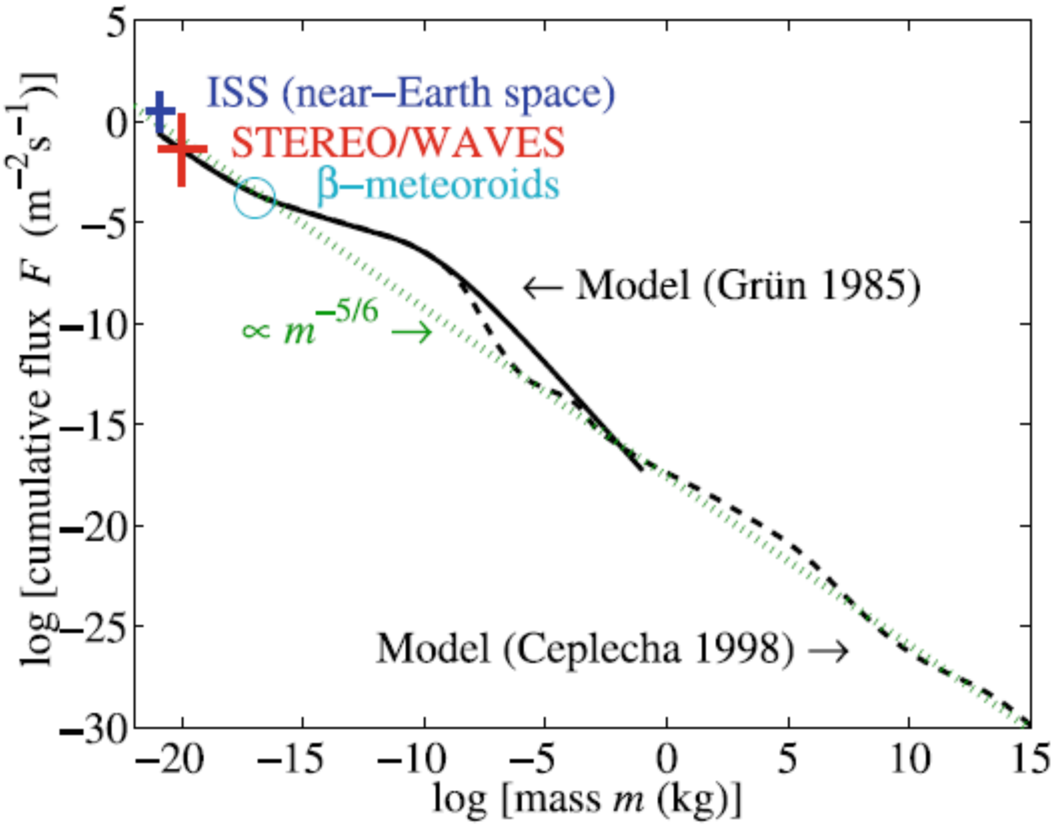
McCord et al., 2011

Creation of a Veneer

- Total polar water source rate of 2S or 6×10^{18} H_2Os/sec
- Assume water distributed quasi-evenly over the mid-latitude region between 70-85^o latitude (a band of 10^{12} m^2 in the each of the north and south)
- Water mid-latitude infall becomes **F_w~ 3×10^6 H_2Os/m^2-s** (i.e., down-pouring rain from polar craters)
- On ~500 sec trip from pole, about 0.5% of waters photo-dissociate to OH making **F_{OH}~ 2×10^4 OHs/m^2-s**
- OH sticks to the surface until it photo-dissociates [Crider and Vondrak, 2000]
- **In as steady-state, OH influx has to equal OH losses: F_{OH} ~ N_{OH}/ τ_{OH}**, making N_{OH} ~ 2×10^{11}/m^2 or **about ~ 1-10 OH's on each 1 micron grain**
- **Molar fraction of water ~ 3×10^{-8}** …much lower than observed by M^3 IR
- Polar fountain contributed to the veneer, but not dominate its formation….some other process

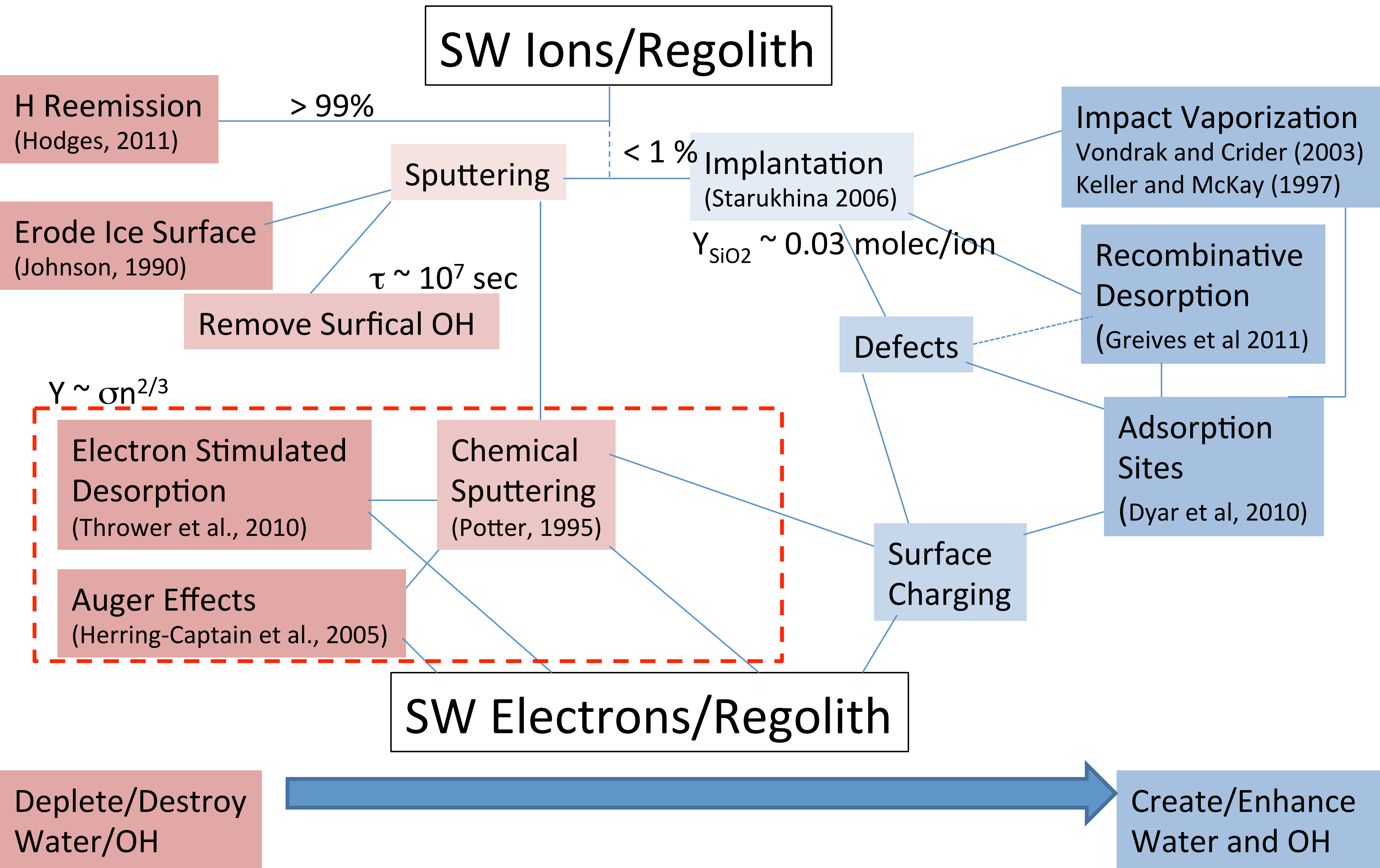
Impactor Flux Levels

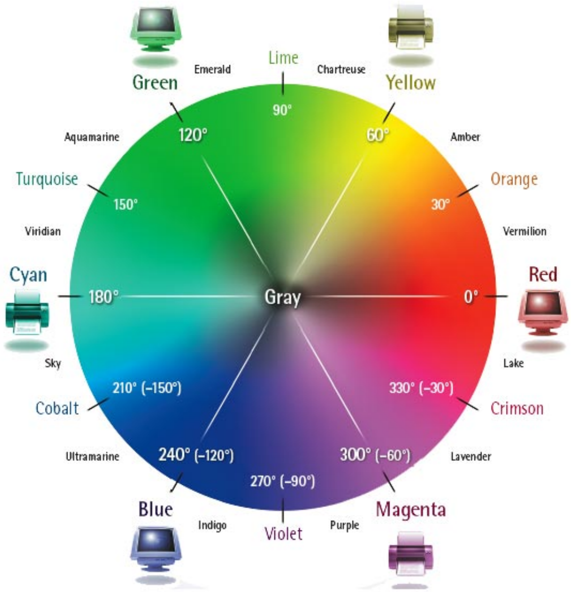
Figure 5 Flux of particles of mass greater than m. Our result, the ISS detection (Carpenter *et al.*, 2007), and the β meteoroids detected by *Ulysses* (Wehry and Mann, 1999) are superimposed to the interplanetary dust flux model (solid line, Grün *et al.*, 1985) and to the model derived from meteor and small solar system object observations (dashed, Ceplecha *et al.*, 1998). The green dotted line is a flux $\propto m^{-5/6}$, as expected for collisional fragmentation equilibrium (adapted from Meyer-Vernet, 2007).



Physical/Chemical

Interaction: Plasma/Regolith Interface





Lime
Emerald
Chartreuse
Green
Yellow
90°
120°
60°
Aquamarine
Amber
Turquoise
Orange
150°
30°
Viridian
Vermilion
Cyan
Red
180°
Gray
0°
Sky
Lake
210° (–150°)
330° (–30°)
Cobalt
Crimson
240° (–120°)
300° (–60°)
Ultramarine
Lavender
270° (–90°)
Blue
Magenta
Indigo
Purple
Violet